

E.6. PROBABILITY OF INTERFERENCE EFFECTS

Steady-state analyses assume that the conditions are invariant with time, with the means and variances of parameters taken over long time intervals. A worst case analysis assumes that all of the parameters except thermal noise (including interference noise density) are deterministic at their worst possible values, and lets the long term noise statistics establish the relevant thresholds. Examples are derivation of bit error rates and accuracy degradation or carrier loss-of-lock thresholds.

MSS interference does not fit this standard model. First, the event duration is at most a few seconds; a duration short compared to the steady-state hypothesis. Second, all of the parameters will vary from pass to pass. It is highly unlikely that all parameters will be at their worst possible state on any individual pass. Therefore, a conservative probabilistic analysis is appropriate. **A probabilistic approach is consistent with the principles of Required Navigation Performance which recognize that absolute perfection is not achievable and is not required for safe operation. RNP performance is, in fact, defined in terms of risk probabilities.**

The RNP Continuity requirement for CAT-I is 1×10^{-5} per approach, implying that systems are allowed to lose continuity due to navigation system related events approximately once per 100,000 approaches.¹⁰ In this context an RFI event whose probability is small compared to the total should be acceptable.

E.6.1 MSS - GLONASS Coupling

The aviation community has insisted that only worst case analyses be used to determine if harmful interference can occur. It is the view of the MSS participants that worst case analyses can serve as a screening mechanism to eliminate clear instances of non-interference potential, but that a dynamic and/or probabilistic analysis should be used in cases where the worst case screening threshold is not met. A dynamic analysis takes into account the change in path loss and aircraft antenna gain due to aircraft movement relative to a potentially interfering ground mobile transmitter. A probabilistic analysis accounts for the variation in all the parameters that may occur from one approach to another.

E.6.1.1 Worst Case Coupling

A worst case analysis assumes that all of the link budget parameters are at values that cause the resulting link margin to be at its least value. Both analyses in Section E.3 are worst-case, albeit with different assumptions.

- The reference received navigation signal power is at its absolute minimum for all in-view GLONASS satellites.
- The GNSS receiving antenna gain toward all GLONASS satellites is taken at its worst value at the worst elevation angle.

¹⁰ It may be noted here that the GPS/WAAS MOPS only requires the avionics to demonstrate MTBO = 5000 hours, using dual-string equipment for air carriers, yielding a hardware failure rate of approximately 8.3×10^{-6} per approach. This barely satisfies the overall reliability budget allocated to the navigation system and leaves little margin for other navigation system related failures (such as spacecraft failures, shadowing, etc.). Nevertheless, the indicated specification of 1×10^{-5} per approach will be used for this analysis.

- The GNSS receiving antenna gain directly below the aircraft is fixed at the worst case (highest) expected value.
- The MSS subscriber unit EIRP density is at its maximum specified value in the direction of the aircraft.
- The MSS subscriber is operating on the channel closest to 1610.0 MHz.
- The MSS subscriber is always actively talking to a companion satellite (cellular service is not available).
- An MSS terminal is always located directly at Decision Point of the flight path, directly under the aircraft, which is at its minimum RNP altitude for the phase of flight analyzed. For the aviation budget, the MSS terminal is located at the highest possible point allowed by the OCS (as if it were at the top of a tree, chimney or flagpole). For the MSS budget, the MSS terminal is located 30 feet above the touchdown altitude (encompassing the vast majority of all surveyed terrain).
- The $C/(N_0+I_0)$ threshold is at its highest value.

E.6.2 Probability Analysis

The individual link parameters are rarely at their worst values and the probability of all of them simultaneously being worst case is essentially zero. Annex 1 describes a method to analyze the likelihood that all of the parameters together will cause a given margin to be exceeded or will cause a given probability of cycle slipping, assuming that potential interfering emissions are present. When combined with an analysis of the probability that an MSS terminal will be transmitting and close enough to potentially cause harmful interference, the total probability can be estimated.

The method consists of choosing or deriving a Probability Density Function (PDF) and mean for each variable, computing the joint PDF by convolution of the individual PDFs and calculating the Cumulative Distribution Function (CDF) for the probability of cycle slip versus the mean C/N_0 . Table E.6-1 lists the variables, their means and the assumed worst case PDF range and distribution type for each variable. See Annex 1 for a complete explanation of the entries.

Table E.6-1: Variable Parameter Means and PDFs

Variable	Mean	PDF Peak-peak Range	PDF Type
Cref, dBW	-159	4	Uniform
Gglonass, dBic	-0.5	3	Uniform
G ground mobile, dB	-12	4	Uniform
EIRPmss, dBW/MHz	-60	-3, +7	Triangular (Note 2)
Rx implementation loss, dB	1.5	2	Uniform
Cycle Slip C/Not, dB-Hz	N/A.	N/A.	3rd order PLL

Note 1. See Annex 1 for explanation

Note 2: 0 for $x \leq -3$; linearly increasing to 0.2 at $x=0$; linearly decreasing to 0 at $x=7$; 0 for $x > 7$.

All of these values are conservative because:

- The GLONASS ICD indicates a Cref range of -161 to -155 dBW versus the assumed -161 to -157 dBW range;
- The aircraft antenna gain toward GLONASS, Gglonass, is assumed to be at 15 degrees even though there is a probability that all satellites are higher than 15 degrees. The antenna gain actually varies less and has a higher mean than assumed at higher elevation angles;
- The MSS EIRP (EIRPmss) PDF will actually be skewed toward the lower end of values when power control distributions are accounted for, especially in the vicinity of airport approaches where obstacles tend to be few and relatively low in height;
- Uniform PDFs are conservative since actual PDFs tend to be clustered around the mean, decreasing toward the extremes.

Table E.6-2 lists the probability of cycle slipping in one second as a function of the mean C/I₀ for these distributions of variables.

Table E.6-2: Probability of Cycle Slipping in 1 Second Versus Mean C/I₀

Mean C/I ₀ , dB-Hz	Pslip/second
30	.02
31	.009
32	3.4×10^{-3}
33	1.1×10^{-3}
34	2.9×10^{-4}
35	6.1×10^{-5}
36	1.0×10^{-5}
37	1.2×10^{-6}
38	1.0×10^{-7}
39	5.7×10^{-9}
40	1.8×10^{-10}
41	2.8×10^{-12}
42	1.7×10^{-14}

The analysis up to this point has assumed that an MSS emitter is present at the worst separation distance and is transmitting as the aircraft passes overhead. These are highly unlikely events. The probability of a transmitting MSS emitter being present has been analyzed using the following conservative assumptions:

- A total of 3 million MSS subscriber units throughout the US vehicle population of 150 million, yielding a ratio of 1 MSS unit per 50 vehicles;
- Vehicles are on a multi-lane urban highway within the threat radius of an aircraft passing over the highway, yielding the average number of MSS equipped vehicles (out of 100) to be $N = (100)(.02) = 2$;
- The average MSS unit probability of being active during the busiest hour is 0.015, the same as the cellular telephone average during the peak busy hour.
- The probability of a call being via satellite is 0.1 and via cellular is 0.9. Most of the MSS terminals have cellular capability and urban areas (airport locations) have cellular coverage.
- The probability that the terminal user is talking, voice activating the transmitter, during the period of maximum interference coupling is 0.6.

The probability of an MSS unit being present and transmitting under these conservative conditions is $(2)(.015)(.1)(0.6) = 0.0018$.

Table E.6-3 contains the link budget calculations for the mean C/I₀ for CAT-I approaches using the MSS link budget conditions. The corresponding probability of cycle slipping assumes that an MSS unit is present and transmitting is listed from Table E.6-2. The probability of a cycle slip is $< 1 \times 10^{-10}$. **The total probability of a cycle slip due to MSS emissions is $< 2 \times 10^{-13}$, a totally negligible value.** To put this in perspective, the FAA's Aviation System Capital Investment Plan projects approximately 200 million aircraft operations per year (takeoffs and landings) in 2007 throughout the entire National Airspace System. Using this level of activity as a baseline, further assuming that every aircraft is equipped with a hybrid GPS/GLONASS/WAAS receiver, uses it for every approach and that each approach relied upon GLONASS satellites, **the mean time between cycle slip events due to MSS emissions would be 2500 years.**

E.7. GPS/WAAS ANALYSIS

The aviation participants claim that an MSS EIRP power density of -70 dBW/MHz is required to protect GPS/WAAS. The MSS participants believe that there is substantial margin available. Table E.7-1 provides a side by side comparison of the aviation and MSS link budgets. The aviation budget uses WAAS word error rate as the limiting parameter. The MSS budget uses GPS continuity loss alerting as the limiting factor.

Table E.6-3: Mean C/I_o and Probability of Cycle Slipping

Parameter (mean)	Units	CAT-I
Carrier Power, ref.	dBW	-159
Antenna Gain	dBic	-0.5
Correlator Loss	dB	-1.5
Received Carrier Power	dBW	-161.3
MSS EIRP	dBW/MHz	-60
Separation distance, min.	feet	150
Path Loss @ -90 deg. el.	dB	69.6
Aircraft antenna gain	dBic	-12
Interference I _o	dBW/Hz	-201.6
Mean C/I _o	dB-Hz	40.3
P(cycle slip) if MSS unit present & on		$<1 \times 10^{-10}$
P of MSS unit being present & on		1.8×10^{-3}
P _{total}		$<2 \times 10^{-13}$

E.7.1 Carrier Reference Power

The aviation participants state that the worst case reference power should be used in the calculations. The WAAS reference power is -161 dBW into a +3 dBi linearly polarized antenna. The corresponding power into a circularly polarized 0 dBic reference antenna is -161 dBW.

The MSS participants budget uses a worst case GPS satellite reference power of -160 dBW, because the GPS signal is more appropriate to the calculation.

E.7.2 Correlator Losses

The aviation participants claim that the correlator losses can be as high as 2.5 dB.

The total loss of a commercial-quality receiver should be less than 1.6 dB.

E.7.3 Thermal Noise Temperature

The aviation participants assume a system noise temperature of 500 K, or a noise power density of -201.6 dBW/Hz.

A high quality antenna and receiver at these frequencies should have a system noise temperature of less than 350 K, or a noise power density of -203.1 dBW/Hz.

E.7.4 Threshold $C/(N_0+I_0)$

The effective threshold of the receiver is specified in terms of the sum of the thermal noise power density and the interference power density. This threshold is determined by the most sensitive parameter that might affect the navigation output of the receiver. There is agreement that wideband interference behaves like thermal noise of the same density.

The aviation participants assume that the interference duration is long enough to disturb the integrity monitoring output of the receiver. The required $C/(N_0+I_0)$ under these conditions is claimed to be at least 30 dB-Hz, corresponding to word error rate = 1×10^{-4} . The criteria used is that no more than three consecutive WAAS word errors are allowed before integrity is considered lost (i.e., at least one out of four consecutive words must be received correctly). Four words are received in 4 seconds.

The maximum interference is definitely not present long enough to be considered steady state. The aircraft antenna coupling in the direction of a ground mobile emitter varies from minimum to maximum at a rapid rate as the antenna downward lobes pass over the emitter. Maximum coupling occurs for at most a fraction of a second. Thus there is no possibility of causing three consecutive word errors. WAAS word error rate is not the correct criteria. Figure E.7-1 shows the transient $C/(N_0+I_0)$ versus time using the parameters in the aviation budget. The aircraft speed is 100 knots.

GPS continuity loss is the correct criteria to use. Such a short transient will not affect code tracking accuracy, but it might affect carrier smoothing accuracy. The effect is caused by carrier cycle slipping which may cause pseudo-range jumps in the navigation output from the sensor. These jumps are detectable, permitting a continuity alert to be issued if the errors cannot be corrected in the alert time limit of 5 seconds. Choosing a threshold cycle slip rate of 1 in 10,000 per second and using the simulation results of Appendix D, Figure D-3, the corresponding $C/(N_0+I_0)$ is 28.5 dB-Hz.

E.7.5 Antenna Gain Toward an MSS Emitter

The aviation participants assume that the aircraft antenna gain in the direction of the ground interference is -10 dBic.

As in the analysis for GLONASS, the evidence indicates that high quality antennas should be capable of considerably lower back-lobe gain. A value of -12 dBic is conservative, especially since it is assumed to occur at the shortest possible separation distance.

E.7.6 Margin Results

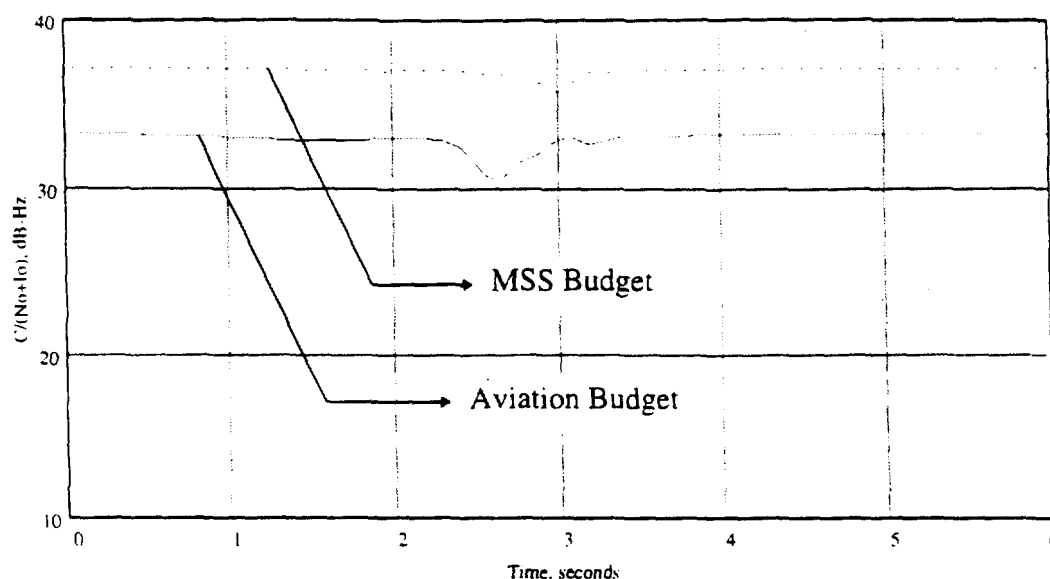
The aviation link budget has a margin of 5.6 dB against interference and 3.6 dB against thermal noise. This result is primarily caused by the assumptions leading to an extremely low received signal level, a minimally performing receiver, and a high $C/(N_0+I_0)$ requirement based on WAAS, not GPS.

The MSS link budget has an interference margin of 13 dB and an 8.5 dB thermal noise margin. All of the values used in the calculations are based on realistic assumptions at minimal increase in equipment cost and minimal operational impact, and even if some of them are not totally

achieved, there is ample margin for some variances. Hence it is concluded that the EIRP limit of -70 dBW/MHz is more than sufficient and is not necessary for safe Category I precision approach operations. In the context of a local-area augmentation system (i.e., in the absence of WAAS), and assuming a minimum 5 degree elevation mask angle for GPS satellites, an EIRP density limit of -57 dBW/MHz would be sufficient to ensure safe Category I precision approach operations.

Table E.7-1: Category I Link Budget Comparison For GPS
(200' threshold DA(H))

Parameter	Units	Aviation Budget (based on WAAS)	MSS Budget (based on GPS)
Reference Carrier Power	dBW	-161	-160
Rcvr Antenna Gain to s/c	dBic	-4.5	-4.5
Correlator Losses	dB	-2.5	-1.6
Received Carrier Power	dBW	-168	-166
Thermal Noise Density	dBW/Hz	-201.6	-203.1
C/No	dB-Hz	33.6	37.0
Threshold C/(No+Io)	dB-Hz	30	28.5
Threshold C/Io	dB-Hz	32.5	29.1
Threshold Received Io	dBW/Hz	-200.5	-195.1
MSS EIRP Density	dBW/MHz	-70	-70
Bandwidth conversion	dBHz/MHz	-60	-60
Separation Distance	feet	100	100
Path Loss	dB	-66.1	-66.1
Antenna Gain Toward MSS	dBic	-10	-12
Received Interference Density	dBW/Hz	-206.1	-208.1
Margin Relative to Threshold Io	dB	5.6	13

Figure E.7-1. GPS/WAAS Transient $C/(N_0+I_0)$ Versus Time

E.8. SUMMARY AND CONCLUSIONS

All parties support the reliability of safety-of-life aeronautical radio navigation systems. The MSS community has already adopted an emissions standard that is more than sufficient to protect GPS and GPS/WAAS-based navigation in all phases of flight, as well as GLONASS and hybrid GPS/GLONASS and GPS/GLONASS/WAAS -based navigation in en route and terminal area phases of flight. There is disagreement between the MSS and aviation communities regarding the need for lower emissions standards to ensure reliability of GPS/GLONASS/WAAS -based navigation during precision approach.

Unfortunately, a single "correct" maximum emission level does not exist, since it depends on various assumed conditions, such as receiver quality and performance, antenna characteristics (and their interpretation), operational requirements, margin allowance and other factors. The "correct" maximum emission level can span a range of about 20 dB, depending on the conservatism, realism, engineering judgment and other subjective, and possibly emotional, factors that influence the determination of an "acceptable" emission level.

Precision approach is a phase of flight that was not considered when GPS and GLONASS were developed, and for which appropriate standards are still in development and validation. The aviation community is to be commended for its ingenuity in augmenting GPS (and GLONASS) to support this phase of flight. Nevertheless, augmentation is clearly required. Over the last ten years, numerous forms of augmentation have been proposed and studied. These include augmentations to the satellite constellation (of which a hybrid GPS/GLONASS constellation is only one choice), augmentations to the navigation receiver, augmentations to the navigation system as a whole, and ground overlays (e.g., the WAAS and LAAS). Each architectural choice implies different vulnerabilities and different protection requirements.

In the debate surrounding MSS emission limits designed to protect GNSS-based precision approach operations, the aviation community has insisted on applying a set of design assumptions that maximize economic penalty to MSS but offer at best marginal economic benefits to civil aviation. At worst, these assumptions actually increase risk to safety-of-life even in a benign environment. This is an inappropriate basis for framing public policy. It also ignores the very real threat of RFI from other sources, many of which are uncontrollable in a regulatory sense.

The MSS community has been proactive in proposing solutions to the interference issue between MSS and GNSS. Based on testing initiated as a result of discussions in RTCA, the MSS community has recently committed to a 4 dB reduction in EIRP density emissions at 1605 MHz. This does not come for free, but the shift is technically achievable with acceptable economic penalty, and is therefore adopted as a means to achieve compromise. INMARSAT notes the 4 dB reduction in EIRP density at 1605 MHz proposed by the MSS community. However, this proposed limit of -54 dBW/MHz at the GLONASS band could have a major impact on existing INMARSAT Services providing distress and safety, as well as non-safety services to a large number of MESs. Notwithstanding this concern with existing INMARSAT systems, INMARSAT agrees that the unwanted emissions limits proposed by the other MSS participants could be met, with acceptable economic penalty, by future MSS systems.

The MSS community has also proposed a number of low-cost, low-risk adjustments that could be made on the part of GNSS receiver specifications, and operational conditions, which collectively lead to satisfaction of GNSS continuity requirements. These include minor improvements in noise floor, correlator losses, etc., and adjustments to antenna gain and separation distance assumptions which are supported by analysis. Other more aggressive techniques also exist and have been studied by the GNSS and aviation communities. These are considered higher-risk and higher-cost, but offer additional benefits relative to navigation system robustness in benign and RFI environments (including sources of RFI that cannot be regulated).

During extensive discussions, RTCA WG/6 has established that interference, when present, is primarily a continuity issue. These discussions have clearly indicated that, although interference may have a minor effect on accuracy, under no conditions does it influence integrity. Further, it is clearly not an HMI concern. The WAAS MOPS state that a navigation system is not to be used if it provides HMI.

The MSS community recommends a combined protection strategy that minimizes overall cost to society, and involves tolerable cost burdens for each community individually. This is technically achievable and economically optimal. It minimizes the degree of adjustment relative to other segments of society which also operate electronic equipment (and which would necessarily have to meet the same out-of-band emissions limits as MSS, in order to ensure safety of flight), and almost certainly leads to a more robust precision approach guidance architecture for all.

E.9. STATUS OF USE OF GLONASS BY AVIATION IN THE USA

Within US airspace, the national policy is to support public-use precision approach until the year 2010 with a combination of ILS, GPS and WAAS. Local-area differential schemes are expected to play a role for Category II/III approaches, and may also play a role in a limited number of Category I locations (local schemes will also continue to be approved for private/special use). **GLONASS is not currently a part of the projected GNSS usage or certification philosophy within the US**, although standards may someday be developed which allow aircraft to employ GLONASS as an adjunct to GPS + WAAS.

GLONASS has real technical and organizational/management shortcomings which limit its near term prospects for precision approach. Some of these are listed in Table E9-1. While these shortcomings may be overcome with time, at this time there are no plans to use GLONASS within the US. The decision to do so, the development and adoption of the necessary standards, the undertaking of the necessary government and industry testing, the development and approval of FAA certification requirements and the development, production and installation of the necessary avionics will take many years. Given the high degree of technical and political uncertainty, it is unlikely the process can be completed within the next decade.

Technology is likely to advance over this time period, both within the aviation community and within the MSS community. Further more, the solutions to some of the shortcomings listed in Table E9-1 may lead to inherently more robust receiver designs. Making decisions now based on today's uncertain circumstances accrues to no one's benefit.

There is no necessity for the cognizant US government agencies to under-take further rule making until such time as there is a clear understanding of the technical and operational requirements and timelines for the inclusion of GLONASS within the US National Airspace System.

Table E9-1: GLONASS Shortcomings**Technical Shortcomings**

Group delay variations across GLONASS frequency plan in receiver front end. These group delay variations are typically sensitive to temperature and aging; hence, they can change significantly as an aircraft is descending on final approach. The effects of group delay variation across the various FDMA'd GLONASS signals under track lead to pseudorange variations that are significant for precision approach accuracy requirements. The aviation community has contended in RTCA that these variations are insignificant or can be calibrated-out in real time; however, European and US manufacturers actually attempting to build GPS/GLONASS receivers for high accuracy applications have acknowledged this is a real issue. One manufacturer believes a technical solution exists, but involves substantial laboratory work to confirm. This solution would substantially increase the cost of a receiver (thereby reducing its cost-effectiveness). Another manufacturer (3S) has a research program under way, but has not reported any positive results. Even if a technical solution is found, there is a serious integrity issue since the real-time calibration method would have to be impervious to failure modes, to a confidence of at least 0.9999999, that could potentially allow an incorrectly-calibrated signal to pass through (RAIM/FDE may not be able to identify an error on the order of a few meters, which is still large enough to cause a problem on a precision approach). No real-time measurement/calibration system developed by mankind to date has ever satisfied such a level of confidence. It should be noted that this is only an issue for precision approach. At RNP levels needed for en route or NPA operations (at altitudes substantially greater than the 100 feet assumed by aviation), calibration is not required and GPS/GLONASS hybrids can be expected to evolve. However, this issue alone implies that it will be years or decades before GLONASS can even demonstrate a laboratory prototype capable of satisfying aviation requirements for precision approach operations.

Two second word length which limits ability to verify short-term integrity via embedded parity checking. This may be significant since some manufacturers of GPS-based avionics have indicated they intend to rely on the short word length of GPS (0.6 seconds) and the associated parity field as a means to help ensure short-term integrity given the short alarm times associated with precision approach operations. A GLONASS receiver would require alternative or modified methods.

Planned reliability of the spacecraft which is less than GPS and which will adversely affect system availability and continuity. GPS barely manages to demonstrate acceptable availability and continuity even with substantially more reliable spacecraft, and with consideration of WAAS. GLONASS in the absence of GPS simply cannot meet the requirements, even with a geosynchronous overlay such as WAAS (and while the GPS/WAAS MOPS specifies a message structure that could potentially support GLONASS correction messages, RTCA has not investigated the technical requirements of a GPS/GLONASS hybrid and the current WAAS procurement includes neither effort nor funding to support GLONASS).

Table E9-1: GLONASS Shortcomings (continued)**Technical Shortcomings (con't)**

Chip duration impairs ranging performance. Because GLONASS chip duration is twice that of GPS, ranging accuracy is 4 times worse at the same relative chip spacing (i.e., one chip) and SNR level (it is proportional to T^2). GPS receivers are already moving to narrow correlator techniques to improve pseudoranging accuracy and minimize multipath errors; GLONASS receivers will have to go to even greater lengths to achieve these benefits and overcome the fundamental shortfall of GLONASS.

Multipath performance. As noted above, GLONASS suffers from a comparative shortcoming relative to GPS with respect to multipath performance. The impact on precision approach applications is currently unknown.

WAAS technical capabilities. The WAAS is currently being developed for augmentation of GPS only (despite the message format developed by RTCA, which allows correction of GLONASS). This \$500M dollar program is not planned to provide a Category I capability until shortly after the turn of the century, with current specifications, budgeting and schedules. Software is being developed for GPS only, and reference stations are being developed for GPS only. To enable GLONASS for precision approach, substantial software modifications will be required at the Monitor Stations and the Central Processing Facility, as well as hardware changes at the Monitor Stations (at least). Software will have to be changed, for example, to account for differing orbits, differing frequencies, differing chip durations, differing message structures, differing integrity determination algorithms, and differing ionospheric calibration routines. Message scheduling software in the CPF will also require enhancement in order to satisfy the larger data throughput requirement for additional satellites, in a limited BW. These changes represent varying levels of difficulty, but will certainly take time to implement and validate once a firm decision is made to proceed, and funds are made available. At the Monitor Stations, hardware changes will also be required to provide additional tracking channels in the reference receivers, additional bandwidth to the CPF, and possibly additional nulling/beamforming capability in the monitor station antennas. Group delay variations may also require real-time calibration, with extremely high levels of confidence given the need to base corrections for precision approach on the result. This list of changes is not intended to be exhaustive.

Table E9-1: GLONASS Shortcomings (continued)**Management Shortcomings**

Lack of rigorous software certification guidelines and controls in GLONASS control segment. Since the control segment is in the serial path providing critical data to the end-user, lack of S/W certification could hamper the ability to certify GLONASS for safety-critical operations.

Uncertain transition timeline to far-term frequency plan.

Uncertain economic and political support for the system.

Spacecraft maintenance procedures which may not be conducive to the high levels of availability and continuity needed for a sole-means navigation system. Spacecraft maintenance and overall constellation health is also related to the level of economic and political support the system receives in Russia -- poor working conditions and lack of rigorous procedures can lead to unexpected problems in the operation of the system, and the level of navigation performance it provides. As an example, in one 30-day period this year, despite official pronouncements that GLONASS is fully operational, over 20 individual spacecraft outages were reported (i.e., "health bit" in the downlink message indicates spacecraft signal is not usable). Some of these individual outages persisted for many days -- a situation that would not be tolerated in the United States. This performance is inconsistent with a sole-means safety-of-life navigation system, although GLONASS could potentially be used as a supplement to GPS.

APPENDIX E. ANNEX 1

MSS To GLONASS INTERFERENCE PROBABILITY ANALYSIS

1. INTRODUCTION

This document presents an analysis of the probability that an active MSS emitter will cause carrier cycle slipping in a well designed GLONASS receiver during precision final approach operations. The analysis treats the link variables as statistical quantities, each defined by a mean and deviation around the mean.

Five of the six link parameters are treated as statistical quantities; the sixth is the free space path loss treated as a constant at a given distance. The five variables are:

- Received carrier power into an isotropic 3 dBi linear antenna, C_{ref} ;
- Antenna gain toward a GNSS satellite, G_s ;
- Antenna gain toward the MSS emitter, G_i ;
- MSS interference EIRP, E_i ;
- Probability of cycle slipping as a function of C/N_o .

2. ANALYSIS METHOD

The analysis method consists of choosing or deriving a Probability Density Function (PDF) and mean for each variable. The joint PDF is computed by convolving the individual PDFs with one another. The joint PDF is then integrated to generate the overall probability of cycle slipping for each value of mean C/N_o .

2.1 Carrier Reference Power PDF

The carrier reference power coupled into an isotropic 3 dBi linear antenna is assumed constant with elevation angle, is uniformly distributed about the mean with peak to peak variation of 4 dB as indicated in the GLONASS Interface Control Document¹¹ (ICD). GLONASS mean reference power is assumed to be 2 dB above the ICD minimum of -161 dBW, or $C_{refmean} = -159$ dBW. The carrier power actually increases with increasing elevation angle by as much as 1.6 dB. This variation is not included, making the resulting distribution conservative.

¹¹ RTCA. "Global Satellite Navigation System: GLONASS", Interface Control Document (Second Wording). RTCA Paper No. 518-91/SC159-317, Circa 1991. This document specifies the minimum C_{ref} as a function of elevation angle and indicates that the minimum level may vary by as much as 4 dB upward. The variation in elevation angle is not included in this number.

2.2 Antenna Gain Toward a GNSS Satellite

Table E(Annex)2-1 lists the minimum and maximum antenna gain as a function of elevation angle. The minimum is taken from ARINC Characteristic 743A, while the maximum was estimated from available measured gain patterns¹². The gain is assumed uniformly distributed between the minimum and maximum at any specific elevation angle.

Table E(Annex).2-1: Antenna gain Toward a GLONASS Satellite

Elevation degrees	Maximum dBic	Minimum dBic
5	-3	-4.5
10	-1	-3
15	1	-2
20	2	-2
90	4	-2

2.3 Probability That a Satellite is At a Specific Elevation Angle

Even though satellites may appear at any elevation angle, it is assumed that the probability is 1.0 that the interfered with satellite will be at the minimum mask angle, in this case 15 degrees. The antenna gain is uniformly distributed +/- 1.5 dB around the mean of -.5 dB.

2.4 PDF of Antenna Gain Toward An MSS Emitter

The antenna gain toward an MSS emitter is assumed uniformly distributed ± 2 dB around the mean, where the mean is taken in the direction of maximum gain toward the emitter.

2.5 MSS EIRP PDF

MSS mobile manufacturers design transmitters so that there is very low probability of exceeding an emission specification limit, since an out of spec condition is costly to repair in a production line. Because the out-of-band emissions are the result of several variable parameters, the PDF can be approximated by a triangular distribution function with a value of 0 at $x = -3$, linearly increasing from a PDF of 0 to a value of 0.2 at $x = 0$, then linearly decreasing to a value of 0 at $x = 7$. The mean of this distribution is 1.1.

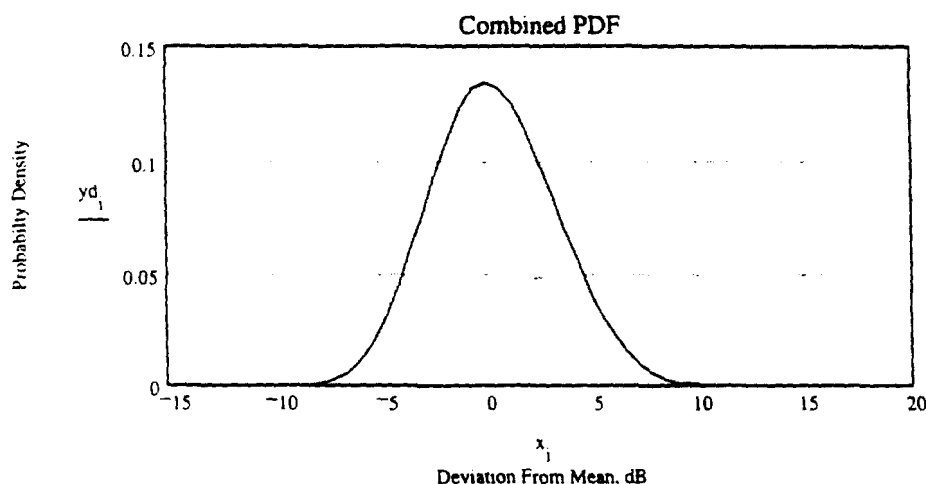
¹² Professor Per Enge, "GPS Aircraft Antenna Patterns". RTCA SC-159 WG on Interference, December 5, 1994. Contour plot of BAC1-11 aircraft GPS antenna gain pattern. William Moyer, "Aircraft Mounted Antenna Pattern Data", presented to RTCA-SC-159/WG-6, 28-29 August, 1995.

2.6 Carrier Cycle Slipping C/I₀ PDF

The cycle slipping C/I₀ PDF is assumed uniformly distributed ± 1 dB about the mean where the mean is selected to include implementation margin relative to theoretical projections.

3.0 C/I₀ PDF RESULTS

Figure E(Annex)-1 plots the joint C/I₀ PDF for all the variables.



4.0 PROBABILITY OF CYCLE SLIPPING VERSUS MEAN C/I₀

Analytic and simulation models for estimating the probability of carrier cycle slipping due to transient interference were developed by the aeronautical community during the course of the SC-159 WG-6 meetings. The analytic model is described in Appendix C, while the simulation model is described in Appendix D. Table E-2 lists the results of these models for a third-order tracking loop, expressed as a mapping function between C/I₀ and slip rate (defined as Pr{slip} per second), based on the analytic results of Appendix C adjusted with a 1.5 dB correction based on the simulation results of Appendix D.

Given a mean C/I₀ based on link budget considerations, and the variation of C/I₀ about the mean as defined by Figure E(Annex)-1, one can calculate the weighted probability of a cycle slip over a one second period. Table E-3 lists the resultant probability of cycle slipping as a function of mean C/I₀.

Because an aircraft in final approach is traveling at a substantial velocity relative to any land mobile terminal, any interference coupled into the GLONASS receiver is transient, lasting at most a few seconds. Computations by independent parties within the RTCA SC-159 WG6 have demonstrated the nature of these transients, whose duration is less than one second as the aircraft worst case down lobe sweeps over the interfering source.

Table E(Annex)-2: Mapping Function Between C/I_o and Slip Rate

C/I _o , dB-Hz	Pr{slip} per second
22	.42
23	.18
24	.05
25	.008
26	8.2×10^{-4}
27	4.3×10^{-5}
28	1×10^{-6}
29	9×10^{-9}
30	2×10^{-11}
31	1.3×10^{-14}

Note: 10 Hz loop bandwidth, 140 Hz envelope detector bandwidth, 3rd order loop

Table E(Annex)-3: Probability Of Cycle Slipping Versus Mean C/I_o

Mean C/I _o , dB-Hz	Pslip/second
30	.02
31	.009
32	3.4×10^{-3}
33	1.1×10^{-3}
34	2.9×10^{-4}
35	6.1×10^{-5}
36	1.0×10^{-5}
37	1.2×10^{-6}
38	1.0×10^{-7}
39	5.7×10^{-9}
40	1.8×10^{-10}
41	2.8×10^{-12}
42	1.7×10^{-14}

5.0 Probability of Carrier Cycle Slipping Equations

Variance of tracking jitter, radians squared:

$$\sigma^2 = \frac{Bn}{C / No} \left[1 + \frac{1}{2C / NoTe} \right]$$

Mean time between slips, seconds, first order loop. Add 2 dB to C/No for 3rd order loop:

$$T_{\text{slip}} = \frac{\pi}{2Bn\gamma} \tanh\left(\frac{\pi\gamma}{4\sigma^2}\right) \left[I_0^2\left(\frac{1}{4\sigma^2}\right) + 2 \sum_{n=1}^{\infty} (-1)^n \frac{I_n^2\left(\frac{1}{4\sigma^2}\right)}{1 + (4n\sigma^2 / \gamma)^2} \right]$$

where I_0 and I_n are Bessel functions.

Loop stress, radians (3rd order loop)

$$\gamma = \frac{5.67 j_{\text{max}}}{\lambda Bn^3} \quad j_{\text{max}} = \text{max. jerk (0.25 g/sec for WAAS)}$$

Probability of slipping in time t seconds

$$P_{\text{slip}}(t) = 1 - e^{-\frac{t}{T_{\text{slip}}}}$$

Bn is one-sided loop bandwidth, Hz

Te is envelope detector time constant, seconds

λ is carrier wavelength, meters

APPENDIX E, ANNEX 2 INSTALLED GNSS ANTENNA PARAMETERS

This annex was being prepared as Appendix J to the main report by aeronautical and MSS participants in an attempt to bring together in one place several analyses, and reported flight and model measurements concerning performance of GPS antennas installed on aircraft. At the last moment but before the final draft was coordinated, and for unexplained reasons, the aeronautical participants stated that they would not agree to a "bi-partisan" Appendix on this subject. In an effort to assist the reader of the report in understanding the details of an important technical issue, the MSS participants have used then-existing text and completed the document in a balanced manner to be this Annex for its "Perspective."

(E)J.1 Introduction

Several of the link budget items needed to evaluate the susceptibility of airborne GNSS receivers to RFI are related to parameters of the installed GNSS antenna. These items include frequency response, gain pattern, and polarization mismatch. This appendix attempts to list all potentially applicable data regarding these parameters that has been brought before this Working Group.

(E)J.2 Frequency Response

Figures J-1 and J-2 show the frequency responses of four commercial GPS antennas [J-1]. The frequency responses around L1 are expanded in Figure J-2. The responses were determined by measuring the induced voltage at the antenna output when the antennas were subjected to a 1 V/m electric field. Note, as expected, that the response peaks sharply at L1. The induced voltage for frequencies offset from L1 by more than 100 MHz is 80 dB below the peak value at L1. This implies that the power from interfering signals this far out-of-band will be attenuated by at least 80 dB.

(E)J.3 Gain Pattern

The GNSS receive antenna pattern significantly affects both signal and interference levels. Unfortunately, very little measured antenna pattern data for actual aircraft installations is available in the open literature. This Annex discusses the potentially applicable data sets that have been brought before the Working Group.

(E)J.3.1 Pertinent Specifications

Antennas conforming to RTCA/DO-228 GPS/WAAS Antenna MOPS [J-2] must have a minimum signal gain of -4.5 dBic at +5 degrees elevation, the minimum satellite elevation angle for navigation. DO-228 requires that at 0 degrees elevation the gain must be between -7.5 and -2.0 dBic. Maximum gain above 5 degrees elevation must be less than 7 dBic (per DO-228). These values represent reasonable limits based on actual antenna measurements on test stands. The gain for interference signals arriving from below the horizon (negative elevation angles) is unspecified, and is subject to significant influence from several factors related to the aircraft configuration and antenna installation.

(E)J.3.2 Simulation

Simulated gain patterns, based on Geometric Theory of Diffraction (GTD) modeling performed at Ohio State University for three typical aircraft antenna installations in the geometric plane bisecting the aircraft's fuselages are shown in Figure J-3 [J-3]. Of these, two represent different antennas installed above the wings of one general aviation (G/A) aircraft (Piper PA-32), and one represents a single antenna installation on the fuselage (approximately 2 m forward of the wings) of a Boeing 737. Note that, in all depicted cases, the gain decreases sharply as the roll angle increases from 90 degrees (horizon) to 180 degrees (directly below the aircraft).

A recent paper [J-4] used a variant of GTD to develop a uniform asymptotic formula for the creeping wave field in the shadow region of a conducting circular cylinder excited by a source on the surface. The author, Dr. R. Paknys, of Concordia University, Canada, was commissioned by one of the MSS participants (Motorola) to employ the techniques described in his paper to calculate the anticipated gain pattern of a GPS antenna on a flat ground plane and three cylinders whose diameters were representative of two smaller aircraft (i.e., King Air and Canadair) and a representative commercial airliner (i.e., a Boeing 737). The results of Dr. Paknys' analysis are shown in Figures J-4, J-5, J-6, and J-7.

Both simulations provide theoretical confirmation of the measured results obtained in the Pax River flight tests (described below), for both the gain differential (above and below the aircraft horizon) and the effect of polarization on test results. As reported in the Pax River paper, the large negative lobe seen in ground plane measurements of GPS antennas disappears when it is mounted on a cylinder (i.e., a fuselage). However, the simulations differ in how the gain of the antenna below the horizon varies with increasing fuselage diameter.

The simulation data, however, is of limited use because of the fidelity of the GTD technique and since it does not account for diffraction from small-scale structures on actual aircraft including landing gear, other antennas, etc.

(E)J.3.3 Scale Model Measurements

One published report on GPS interference studies by Niser and Owen [J-5], includes pattern data on a 1/9 scale model of BAC 1-11 (about the size of a Boeing 737-200 with rear fuselage-mounted engines like a DC-9). The pattern (Figure J-8) was measured at 14 GHz on a frequency-scaled RHCP (right-hand circular polarized) antenna mounted on the top fuselage of the 1/9 scale model just aft of the forward door.

The two paragraphs below represent the view of the aeronautical participants in the Working Group regarding this data.

Note that gain contours at the indicated values are on the boundary between indicated adjacent areas (i.e., the -5 dBic contour is the boundary between right- and left-slanted zones). The pattern has good coverage in the upper hemisphere, but high gain sidelobes centered at -60 degrees elevation ahead and either side of the fuselage. These sidelobes have approximately the same gain as that for the minimum elevation satellite (0 dB rel. gain) and substantial angular extent. Comparison to the peak upward gain shows that aircraft structure diffraction has limited the installed GNSS antenna to about a 10 dB minimum front-to-back gain ratio.

The angular direction for the strongest sidelobe will, in general, be different on different aircraft depending on structure diffraction details. However, it can be generally assumed that the sidelobe will be in a sufficiently downward direction to offer a relatively short path length to ground-based

interference. In the BAC 1-11 model test, the path length to the ground in the maximum sidelobe direction is 15% (1.2 dB) longer than to a ground point directly below the aircraft, but the antenna gain in the sidelobe is higher by about 10 dB. Given the pattern complexities of actual aircraft and the need to establish a reasonable bound on side- and backlobe gain, a conservative assumption for the GNSS interference analysis uses the 10 dB front-to-back gain ratio limit. That leads to the outcome that the minimum elevation satellite and interference gains are equal.

The paragraph below represents the views of the MSS participants regarding the Niser/Owen data in Figure J-4.

There are several problems with the BAC 1-11 model data. First, the published report does not include a description of the test procedure nor the apparatus used in the test.¹³ Second, the 5 dB granularity of the presented data¹⁴ means that measured results of 9 dB difference appears the same as a 1 dB difference. Third, and most importantly, the presented data is inconsistent, as can be seen by a consideration of the gain at -90 degree elevation. In this type of "mercator" presentation, all the data at -90 degrees elevation (the "south pole") should be the same. However, as can be seen in Figure J-8, the antenna gain varies between the -5 to -10 dB level all the way to below -20 dB.

(E)J.4 Polarization Mismatch

Another antenna parameter is sidelobe polarization mismatch loss. The Niser/Owen data lack sidelobe and backlobe polarization sense information. However, for a RHCP interference source, no polarization mismatch loss allowance should be used; it has already been included in the measured GNSS antenna gain. For an LHCP source it is imprudent to allow any mismatch loss because some GNSS backlobes could conceivably be LHCP due to reflection off metal aircraft structural elements. A vertically polarized source (e.g. an antenna at low elevation angles) would at most have 3 dB polarization loss to a circularly polarized backlobe. However, an interference source could have fairly good circular polarization at the high elevation angles for a short range GNSS encounter during a precision approach. Given the above considerations, the analyses in this report use 0 dB polarization mismatch loss.

Note: The sections below were prepared by MSS participants and was not concurred in by aviation participants.

(E)J.5 Full Scale Aircraft/Antenna Tests

As noted above, there is no specification that defines installed GPS or GNSS antenna gain below the horizon of a civilian aircraft. In connection with the growing interest in the effect of ground-based interference (including multipath) on GPS navigation performance, several measurement activities have been undertaken to obtain information on GPS antenna performance. The two activities reported below are:

- In-flight measurements to investigate the origin of the "wormhole" and interference from TV transmitters. This was performed by the Naval Air Weapons Center (NAWC-Patuxent River) under the joint sponsorship of the FAA, DOD and Transport Canada Aviation (TCA).

¹³ The testing station has been disassembled and cannot be viewed.

¹⁴ The presentation of the test data is mislabeled in that the ordinate labeled "AZIMUTH" is clearly the elevation angle.

- Static measurements on a large section of a Boeing 727 fuselage, performed by McDonnell Douglas, sponsored by an MSS participant (Globalstar).

(E)J.5.1 In-Flight Measurements by NAWC - Pax River

Laboratory and in-flight measurements of GPS antenna gains were conducted in support of an effort to investigate the potential for interference to GPS-based navigation arising from harmonic transmissions of television transmitters. The purpose of these gain measurements was to "calibrate" the aircraft installation of the GPS antennas prior to the subsequent flight campaign of evaluating interference from operational television transmitters in the U.S.

Three different aircraft, the Navy's ES-3A, an FAA King Air BE-300 and TCA's Canadair Challenger, each specially instrumented for the GPS interference measurement task, were used in the testing campaign. Below, in Sections (E)J.5.1.1 through (E)J.5.1.4, are extensive excerpts from the report of this FAA/DoD/TCA - sponsored testing effort from a paper [J-6] presented at the ION-95 Conference.

(E)J.5.1.1 Test Description, Results and Discussion: Aircraft Antenna Tests

Antenna pattern (gain) and polarization effects play a significant role in the aircraft GPS system's susceptibility to interference. The GPS signals are transmitted from the satellites using Right-Hand Circular polarization (RCP). The general case of elliptical polarization can be described as the combination of the two linear components, vertical polarization (V-Pol) and horizontal polarization (H-Pol), translating along the propagation axis. Circular polarization is that special case of elliptical polarization where the linear components meet all of the following criteria: (1) space orthogonality, (2) phase quadrature (90 deg), and (3) equal amplitude. A practical RCP antenna will not exhibit perfectly circular polarization characteristics, especially off-boresight (the same is true of the transmissions from the GPS satellites). When two CP antennas are used for transmit and receive, the elliptical nature of their responses will result in polarization mismatch loss. This loss will not necessarily match that expected using antenna gain measured with a CP source! For example, two antennas with axial ratios of 8 dB would show approximately 0.75 dB loss each against a perfect CP radiator. However, the actual mismatch losses between the two antennas will range from 0 dB with ellipses aligned to approximately 3 dB with ellipses fully misaligned. A common technique to address this problem is to measure the antenna pattern with a rotating linear source.

(E)J.5.1.2 Antenna Ground Plane Characteristics

Figure (J-9) shows a pattern measured at Patuxent River's GRATF with the TCA dual-band antenna on a 4 ft. circular ground plane. The 90 deg. "waterline" is in the ground plane, while 0 deg. represents the overhead direction (i.e., pointing up). Horizontal, vertical, and rotating linear patterns are shown. In the region from -45 deg. to +45 deg., where the horizontal and linear components are roughly equal, the RCP response of the antenna will be close to 3 dB higher. Note that from 30 deg. above the horizon to -15 deg. below that the V-Pol response is much higher than the H-Pol by 7.6 dB or more, the RCP response of the antenna will be less than the V-Pol (but not by more than 3 dB). The rotating linear plot can be used to illustrate the elliptical nature of the response. When the rotating linear plot fills but does not overlap the V-Pol and H-Pol responses, the tilt angle will be orthogonal (e.g. -90 deg. or 90 deg.) and the difference in the V-Pol and H-Pol responses will represent the axial ratio in dB (sign of the axial ratio is negative for RCP).

Although hard to discern in the figure, the H-Pol response is almost non-existent from 0 deg. until the "back lobe" at 180 deg. In contrast, the V-Pol response exhibits gradually decreasing gain until

about -30 deg., and lobing thereafter until the back lobe is reached. On the flat ground plane, the "back lobe" is the strongest response at angles below the ground plane, approximately 10 dB below the gain above the horizon.

When this antenna is installed aboard an aircraft, the general relationships of V-Pol, H-Pol, and RCP will remain. When mounted on a cylindrical surface rather than a flat plate, the pattern shown above will tend to lose some gain above the horizon, lose the distinctive back lobe, and distribute the energy in the areas in-between. The H-Pol response will extend further below the horizon but still show a rapid cutoff. The V-Pol response will show an even more gradual loss of gain as the angle below the horizon is increased.

(E)J.5.1.3 In Flight Patterns

Unlike ground patterns which produce completely orthogonal and repeatable pattern "cuts", the airborne patterns are the result of the aircraft maneuver relative to the ATLAS ground station. This results in a "great circle" pattern where the elevation and azimuth angle will vary through the measurement. In addition, the aircraft may fly longitudinal "porpoise" maneuvers which result in an approximation of an elevation cut. For the passive antenna installed aboard the Challenger, a small 1 watt transmitter was placed in the aircraft, and all three polarizations of interest (V-Pol, H-Pol, and RCP) were measured simultaneously on the ground. During the TCA Challenger flight, angles of bank up to 45 deg. were employed, which allowed the antenna pattern gain to be measured to about 50 deg. below the aircraft waterline.

(E)J.5.1.4 Discussion

Figures [J-10, J-11 and J-12] show plots at differing flight profiles of the three polarization responses measured by ATLAS of the dual-band antenna installed aboard the Challenger. The solid line in the figures represents RCP, the dotted line V-Pol, and the dashed line H-Pol. On the "great circle" patterns, the depression angle is given in parentheses.

For signals at the aircraft waterline or below, the primary antenna response is to V-Pol. The V-Pol gain ranges from 0 to -3 dBi at the horizon, dropping to -5 to -8 dBi at -15 deg., and -10 to -12 dBi at -30 deg. The H-Pol response is only -8 to -12 dBi at 15 deg. above the horizon, dropping to -15 dBi at the horizon, and may be as low as -20 to -25 dBi at only -30 deg. It is clear that horizontally polarized signals (such as TV) are significantly attenuated in the antenna pattern (relative to the satellite energy received at 0 dBi), as much as 10 - 15 dB for angles at or slightly below the waterline of the aircraft. In contrast, vertically polarized signals may only receive 2 - 5 dB of attenuation for shallow angles.

In the case of television, it is interesting to note that in the U.S., H-Pol was chosen for TV transmissions because most of the potential interferers were V-Pol (taking advantage of antenna cross polarization losses). Conversely, V-Pol was chosen in the United Kingdom for its superior propagation characteristics. (*Footnotes omitted*)

Since the above ION-95 paper did not present all the measured antenna gain information, additional antenna gain data on banked turns and "porpoise" run flights were made available, on request, to interested SC159-WG/6 participants. Using data only for Right Hand Circular polarized patterns, a composite plot of "worst-case" results was prepared. "Worst-case" in this instance was determined by identifying the angle below the aircraft using only the gain peaks of the individual lobes and their location. Two plots are presented in Figures J-13 and J-14, which represent the test results from the antennas as the aircraft went into the bank and leaving the bank, thereby providing data on antenna gains "looking" forward and aft. For convenience, the Niser/Owen data, as interpreted by

Per Enge in a January 1995 presentation to WG/6, is included in these plots for comparison purposes. Figure J-15 is a representative output of the Pax River data that was used to create Figures J-13 and J-14.

(E)J.5.1.5 Discussion of Figures J-13 and J-14

The results of the Pax River in-flight GPS antenna tests from all three aircraft show that the highest peak gains were -16 dBi in the range of slightly greater than -30° to -60° below the aircraft horizon. Unfortunately, no flight tests were run that provided data for angles between -60° and -90° . However, theory and all data, other than that of the Niser/Owen paper, show that the gain at these lower angles would be lower than those at -30° to -60° . Thus, using -30° to -60° data is quite conservative.

It should be noted that the installed antenna gain at low elevation angles above the aircraft horizon is often somewhat lower than that specified in the MOPS. A review of the Pax River data shows that at 5° elevation angles, measured gain generally is between 0 and -8 dBi and at 15° elevation angles between -2 and -5 dBi. Thus, the worst case, static gain differential between a GPS signal at a 5° elevation angle (-8 dBi) and an interfering transmission from the ground at 30° to 60° below the aircraft horizon (-16 dBi) would be 8 dB and at a 15° elevation angle the differential would be 11 dB. As noted above, the gain differential for between -60° and -90° would be greater.

It should also be noted that the peak gains shown in Figures J-13 and J-14 were generally associated with spike-like lobes that would exist at the receiver input for so short a time period that harmful interference might not be caused to the navigation function during a precision approach.

(E)J.5.2 McDonnell Douglas Tests

The McDonnell Douglas Radar Measurement Center was commissioned by Qualcomm (on behalf of Globalstar) to perform GPS antenna gain measurements. The test procedure and results were reported to WG-6 in late August 1995.

The tests were performed in an RF anechoic chamber using two high quality, commercially available GPS antenna (Commant and Ball Aerospace) when mounted on a 24 foot long segment of a Boeing 727 fuselage (12 feet in diameter). The lower one-third of the fuselage was removed. Figure J-16 illustrates the test configuration. Figures J-17, J-18 and J-19 are the results of the antenna gain tests at 1575.5 MHz.

It can be seen that these antennas meet the minimum gain requirements of the DO-228 GPS antenna MOPS at and above 0° elevation. Moreover, it can be seen that the relative gain between the $+5^{\circ}$ elevation gain and -60° to -90° gain is minimum of 11 to 12 dB, and the difference is generally much greater. At 15° elevation angles, the gain differential increased by 3 to 5 dB so that it would be at least 14 to 17 dB.

(E)J.6 Summary

In summary, the results of in-flight tests, static testing on a large section of fuselage and theoretical analysis support a conservative conclusion that there is a minimum of 8 to 11 dB gain differential in GPS antennas between the gain at a 5° and 15° elevation angles respectively and peak lobes 30° to 60° below the aircraft horizon and even greater differentials to peak lobes 60° to 90° below the

aircraft. Moreover, the question of the time the GPS receiver is subject to an interfering ground signal in a peak gain lobe needs to be evaluated.

(E)J.7 References

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